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Mediated Modeling of the Impacts of Enhanced UV-B Radiation on Ecosystem Services

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ABSTRACT

This article describes the use of group model building to facilitate interaction with stakeholders, synthesize research results and assist in the development of hypotheses about climate change at the global level in relation to UV-B radiation and ecosystem service valuation. The objective was to provide a platform for integration of the various research components within a multidisciplinary research project as a basis for interaction with stakeholders with backgrounds in areas other than science. An integrated summary of the scientific findings, along with stakeholder input, was intended to produce a bridge between science and policymaking. We used a mediated modeling approach that was implemented as a pilot project in Ushuaia, Argentina. The investigation was divided into two participatory workshops: data gathering and model evaluation. Scientists and the local stakeholders supported the valuation of ecosystem services as a useful common denominator for integrating the various scientific results. The concept of economic impacts in aquatic and marsh systems was represented by values for ecosystem services altered by UV-B radiation. In addition, direct local socioeconomic impacts of enhanced UV-B radiation were modeled, using data from Ushuaia. We worked with 5 global latitudinal regions, focusing on net primary production and biomass for the marine system and on 3 plant species for the marsh system. Ecosystem service values were calculated for both sectors. The synthesis model reflects the conclusions from the literature and from experimental research at the global level. UV-B is not a significant stress for the marshes, relative to the potential impact of increases in the sea level. Enhanced UV-B favors microbial dynamics in marine systems that could cause a significant shift from primary producers to bacteria at the community level. In addition, synergetic effects of UV-B and certain pollutants potentiate the shift to heterotrophs. This may impact the oceanic carbon cycle by increasing the ratio of respiratory to photosynthetic organisms in surface waters and, thus, the role of the ocean as a carbon sink for atmospheric CO_2. In summary, although changes in the marine sector due to anthropogenic influences may *affect* global climate change, marshes are expected to primarily be *affected by* climate change.

INTRODUCTION

Mathematical modeling has historically been the province of experts (1). This is fine for addressing technical problems within a discipline. But when applied to policy questions, which inherently span several disciplines and involve stakeholders with nontechnical backgrounds, the modeling approach is severely limited. From a policymaking perspective, the models usually become quite complex and it is difficult to lucidly communicate results (much less the underlying logic of the models) to decision makers (2). Models derive their credibility from two distinct sources: the technical ability of the model to reproduce measured observations, and the degree of stakeholder buy-in of the assumptions and the model construction process. In scientific disciplines the model construction process is often taken for granted. But in policy-relevant modeling it is often the most crucial source and requires special attention. Achievement of the necessary level of buy-in among the diverse stakeholders affected by a policy problem requires that the stakeholders participate in the modeling process, from defining the conceptual problem to analyzing scenarios. We focus on the participatory approach to research and model building and evaluate a collaboration between scientists and local stakeholders in which the impacts of enhanced UV-B radiation (290–320 nm) on ecosystem services are examined.

The emission of anthropogenic chlorofluorocarbons is causing the depletion of stratospheric ozone and resulting in an increased

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transmission of UV-B through the atmosphere. The effects are greatest at polar latitudes but they are also observed in the middle latitudes. The problem will worsen before it improves in approximately 2050. Compared with visible light, UV-B is more energetic and stimulates diverse photochemical reactions (3). Because of ozone depletion in recent years, increased UV-B is an added stress to natural ecosystems. The effects of UV-B on organisms are mostly deleterious, because of damage to DNA and cellular proteins that are involved in biochemical processes, and they affect growth and reproduction. Understanding the effect of UV-B on ecosystems involves knowledge of more than the effect of radiation on individual species or at trophic levels, given that alteration of system interactions can exacerbate, diminish or sometimes reverse known physiological damage. What is known originates from small-scale experiments (4). The role of these effects in large-scale settings and whether they affect the services ecosystems provide to humans are not known. We describe a modeling project in which scientists and stakeholders worked together to produce a model that addresses these questions. We discuss both the mediated model-building process and the model that resulted from that process, because of the importance of both factors. We spend significantly more time on the process, however, because it is more unique.

One reason for using mediated modeling to address the socioeconomic impacts of UV-B radiation is that this type of modeling is geared toward understanding the systems level relationships involved in complex issues. The strength of this modeling approach does not lie in precise prediction of future outcomes. Rather, it provides a framework to understand the most important parts of the problem by linking the known factors to our best available knowledge and defining the unknown factors in a comprehensive way.

METHODS

Mediated modeling is a process of facilitated model building in which stakeholders are involved in all aspects and steps (5–8). The stakeholders decide what goes into the model. They collaboratively construct the model and therefore understand the value (and limitations) of the findings of model simulations. This process often helps structure the discussion and analysis of a complex problem.

The goal of this component of the project was to construct a simulation model of the socioeconomic impacts of UV-B radiation. Mediated modeling was used as the method to construct a simulation model. The stakeholders included scientists who were affiliated with the Inter-American Institute for Global Change (IAI) and had backgrounds in UV radiation, aquatic ecosystems (marine and marsh) and ecosystem modeling and local stakeholders who worked for the government or had backgrounds in education, the tourism industry or medicine. During the first mediated modeling workshop (duration, 4 days) a qualitative scoping model was developed and a list of data requirements to be gathered during the next four years was created. Three years later a second workshop was performed to finish and evaluate the final model.

The socioeconomic impacts of UV-B radiation are difficult to pinpoint because of the lack of established causal relationships. The nature of this type of study prohibits an experimental design and control groups are hard to locate. Historical observations and time-series data provide some insight but have to be related to other trends.

We chose to apply the mediated modeling approach. The three stages suggested by van den Belt (1) involve preparation, workshop participation and follow-up observation (Table 1).

Much of the focus of this research program was on latitudinal differences and experiments were performed at several different locations in the Americas. The selection of Ushuaia, Argentina, as the location for a collaboration with local stakeholders was based on two factors. First, it is in an area with large UV-B fluctuations and, because of the associated social concerns and potential economic impacts, the UV-B problem is most severe. Second, a local research facility was willing to host the workshops and play an instrumental role in stakeholder selection and management. The group of participants was selected locally with conceptual guidance from the mediated modeler.

Table 1. Generic MM approach and subactivities.

Stage	Subactivities
1. Preparation	1.1 Identify stakeholders
	1.2 Set Participant group
	1.3 Conduct introductory interviews
	1.4 Prepare a preliminary model
2. Workshops	2.1 Introduction
	2.2 Problem definition
	2.3 Qualitative model building
	2.4 Quantitative model building
	2.5 Simulation
3. Follow-up	3.1 Tutorial
	3.2 Evaluation

Because of the distance between the mediated modeler and the local participants, the introductory interviews were sent via email in the form of a brief survey. The principle investigators (PIs) prepared and submitted the surveys.

A preliminary model was developed on the basis of reports from the literature and input from PIs and was brought to the first workshop. The final model includes additional data from the literature, results from experiments performed within the IAI project and new ideas developed in the workshops. Concepts in the model were based on classical concepts in marsh and marine ecology. New information acquired during our project on the effect of UV-B was added as applicable (9–12). To quantify the ecological processes in the model, an extensive literature search was done in order to obtain a range of values that were applicable over a wide range of latitudes (4,13–16). All data on the effect of UV-B on salt marshes in the model originated from the IAI project, as this was the first time this topic was studied.

In order to analyze the changes in UV-B radiation between 1970 and 2050, the planet was divided into five regions (Table 4). Worldwide total column ozone data obtained from satellites have only been available since the end of 1978. To calculate the total column ozone during 1970–1978, satellite values from 1979 and trends from ground measurements were used for regions II to IV (17) and data for the polar regions (regions I and V) were inferred from maps built during 1964–1980 on the basis of ground measurements (18). During 1979–2000 the ozone values were calculated from satellite measurements (19). The regional values were obtained by averaging data available for each 5° of latitude.

Seasonal trends were obtained making four groups of 3 months: (1) Summer southern hemisphere (winter northern hemisphere): December through February; (2) autumn southern hemisphere (spring northern hemisphere): March through May; (3) winter southern hemisphere (summer northern hemisphere): June through August; and (4) spring southern hemisphere (autumn northern hemisphere): September through November.

Once the mean total column ozone was determined for the 5 regions and the four seasons, UV irradiances under clear sky conditions for 2000 and 1970 were calculated to obtain the geographic and seasonal mean points, using a Disort 8 Streams Radiative Transfer Code (20). Irradiances were calculated on 15 January, 15 April, 15 July and 15 October at the following latitudes: 72.5°S, 37.5°S, 10°S, 37.5°N and 72.5°N. In the equatorial region (lat 20°S to lat 20°N) the point at 10° was used as the mean point since the geographic means (0°) would give a regional maximum value rather than mean values. Irradiances were calculated in 1 h intervals. Daily integrated irradiances were obtained by integrating hourly values.

To simplify the input into the model we calculated the integrated irradiances for 1970 and 2000 as explained above. The other years were calculated using the radiation amplification factor (RAFs). The RAFs are sensitivity coefficients that relate the decreases in total column ozone in the atmosphere to increases in some measures of irradiance (21):

$$RAF = \frac{\ln(O_3/O_3^*)}{\ln(E^*/E)} \qquad \text{(Eq. 1)}$$

where O_3 and O_3^* are total column ozone 1 and 2 and E and E^* are irradiances corresponding to total column ozone 1 and 2. Then

Table 2. Schedule for the first workshop.

Workshop day	Workshop activity
Day 1	Introduction, software, problem definition and model sectors
Days 2 and 3	Qualitative model, feedback loops and time lags
Day 4	Insert quantitative data readily available, define data to be gathered and evaluate problem definition

$$E^* = \left(\frac{O_3}{O_3^*}\right)^{RAF} * E \qquad \text{(Eq. 2)}$$

The RAF varies with the solar zenith angle (SZA) and, in our case, wavelength. Paired values of ozone variation and daily integrated irradiance were used to calculate the RAFs, corresponding to the SZA of the 5 regions and 4 seasons, for each wavelength between 290 and 400 nm.

The irradiance for 1970 and the ozone for each year (5 regions and 4 seasons) were used to calculate the daily integrated irradiance in the model by means of (Eq. 2).

Past and future daily integrated irradiances. It is estimated that the ozone level will remain near the values 2000 up to approximately 2011 (22). For the model, we kept total column ozone and irradiance values from 2000 through 2010 the same as those from 2000 (recovery will begin after 2011). Models used to calculate future values show some disagreement in the annual percentage of recovery. In general it can be assumed that the recovery will be linear and that ozone values similar to those in 1979 will occur by 2050. The annual change per year (in DU) for each of the 5 regions and 4 seasons was calculated as:

$$Oz_{RSY} = Oz_{RS2000} + [(Y - 2000)^* Ch_{RS}] \qquad \text{(Eq. 3)}$$

where Oz_{RSY} is the total column ozone in year Y for region R and season S (Y ranges from 2010–2050), Oz_{RS2000} is the total column ozone in 2000 for region R and season S and Ch_{RS} is the annual change for region R and season S. Irradiance is calculated with RAF for the period of 1970 through 2000 (see above).

RESULTS AND DISCUSSION

Results are presented in two sections: (1) the workshops and model construction process and (2) model behavior and scenarios. The first section is the more unique aspect of the project. Data available for calibrating and testing the model were extremely scarce: no independent data exist to test the assumptions and data that went into the model. We conclude that the model has strong credibility because of stakeholder buy-in but further technical calibration is needed.

Workshops and the model construction process

First workshop. The first workshop was held in November 2000 in Ushuaia and lasted for 4 full days (Table 2). The workshop was hosted by Centro Austral de Investigaciones Cientificas (CADIC), which is a research center of the National Research Council of Argentina. A representative from CADIC was instrumental in and responsible for identifying and inviting the local stakeholders. Approximately 10 local stakeholders attended the first meeting. Representatives from the tourism industry, an ophthalmologist, a dermatologist, educators, persons from the local government, employees from the fisheries industry, meteorologists and several CADIC technicians attended. PIs involved in UV radiation and UV effects on marshes and marine systems traveled from Canada, the United States and Argentina to attend this workshop. The group provided strong input to achieve the objectives of the project. The local stakeholders presented input from a broad social perspective. However, representation by educators and employees of the fisheries industry was not as strong as initially intended.

Table 3. Questions the model should address, as developed during the workshop in November 2000 in Ushuaia, Argentina.

1. What are the direct and indirect socioeconomic impacts of UV-B radiation?
2. Can we define a synergy or feedback mechanism between different sectors represented in the model; ecosystems (marshes/marine systems), education, tourism?
3. Does the response of UV-B on human health and ecosystem health change with temporal and spatial scale?
4. How does the time lag between CFC release and recovering of the ozone layer and ecosystem responses and human health effects manifest itself?
5. What is the influence of existing policies on local and global level? Are there solutions?
6. Does global warming need to be in the model and if so, can global warming be represented by temperature only?

On day 1 the goal of the workshop was restated, a 10 min exercise to learn participants' names was done and the 4 building blocks of the software (STELLA) were introduced. The first day continued with the formulation of questions the model should answer (Table 3).

The preliminary model was presented to give the participants an idea of how a model might start to evolve. It is common for a group to reject a preliminary model; however, this group decided that the preliminary model provided a reasonable starting point. Although this decision saved time it was harder for the group to "gain ownership" of the model. This manifested itself in the way participants concentrated on their respective specialties rather than on focusing on the system as a whole.

The qualitative model structure that developed over the course of almost 3 days was the basis for a conceptual discussion on days 2 and 3. The time scale was set from 1970 to 2050. The first year (1970) is considered to be in the era before ozone depletion began (on the basis of factors such as ozone layer thickness and UV-B levels). The end point, 2050, is estimated to be the point at which ozone levels return to natural levels; if there is no addition of ozone-destructive compounds, the ozone layer is expected to return to the values before ozone depletion by 2050. The effect of the Montreal protocol (*i.e.* partial recovery) is expected much earlier. The time step was originally set at seasons. In later stages of model development it was observed that the model time step needed to be changed to a monthly time step in order for seasonal effects to be graphically visible. The spatial scale issues are described in Table 4. Five main regions were identified. Within the regions, the space was treated as homogeneous.

The group decided to move the scope of the model beyond the data being gathered at the time by monitoring findings from the literature (23,24), field data and experimental approaches (10). The group pushed the model into unknown scenarios and generated future research questions within a broad context (Tables 5–7).

During day 4 of the workshop available data and information were entered into the model. In addition, the requirements for data gathering during the next 2 years were developed. An example of the data needed from the socioeconomic model sector is presented in Table 8. The list of data requirements for the model was quite extensive. Much of the data were initially thought to be readily available. The workshop closed with a re-evaluation of the

Table 4. Global coverage in 5 latitudinal regions.

Region	Latitude
I. Antarctic	90–55° South
II. Southern temperate	55–20° South
III. Tropical	20–20° North
IV. Northern temperate	20–55° North
V. Arctic	55–90° North

definition of the original problem and "the questions the model should answer."

Several questions were developed at the start of the workshop (Table 3) and evaluated at the end of the workshop. The first question was as follows: *What are the direct and indirect socioeconomic impacts of UV-B radiation?* The first workshop occurred right after the "hole in the ozone layer" (in the Antarctic region) had moved over Tierra del Fuego (mid-November 2000). This event was given a lot of attention in the media and the uncertainty surrounding this issue caused a general sense of fear. There were some indications that tourists were canceling planned travel to Ushuaia out of fear about UV-B radiation. The tourist sector was very concerned about the local economic impact and affect on employment levels.

The dermatologist and ophthalmologist in the group provided support for possible damage by UV-B to health, namely damage to eyes and skin and (arguably) suppression of the immune system. A distinction was made between short-term impacts due to peaks in UV-B radiation and long-term trends due to a gradual increase in UV-B radiation. Because of the recent peak events, the emphasis of the first workshop was on how to accommodate for the peak UV-B events in the model.

A local fisherman suspected a negative impact of UV-B on fish populations. In addition, fishermen are a subgroup of the local population that spends a lot of time outdoors and is subject to and often aware of UV-B radiation. The cost of sunscreen to protect the skin from UV-B radiation was considered to be high.

The second question was as follows: *Can we define a synergy or feedback mechanism between different sectors represented in the model, such as ecosystems (marshes/marine systems), education and tourism?* Ecosystem services were discussed in relation to the marine and marsh systems. In the marine sector the synergy between contamination and UV-B was on the research agenda. For the marsh sector the need for research about the connection between UV-B and increases in the sea level and adjacent plant communities was discussed. Global climate change issues seemed to be the common denominator for marsh and marine issues, although from a different perspective. Although UV-B may have a direct negative impact on marine primary production (25–28), marshes are more affected by climate change in terms of increases in the sea level (29) or El Niño effects (9).

Table 5. Questions for future marsh research.

1. Does the impact of sea level rise override the impact of UV-B on marshes?
2. Does UV-B have an indirect effect on *Juncus* and *Spartina* via the decline of *Salicornia* and its capacity to regulate disturbances?
3. Is the production of seeds of *Salicornia* negatively affected by UV-B?
4. Is the shift from *Salicornia* to *Puccinelia* in Tierra del Fuego due to a UV-B impact or due to a change in sea level?
5. Is the wind a limiting factor to *Salicornia* growth in Tierra del Fuego?

Table 6. Questions for future marine research.

1. How do ecosystems in the Americas respond to natural and enhanced levels of UV-B due to ozone depletion?
2. Are systems sensitive to and/or is a recovery a function of UVR gradients?
3. Are low-latitude systems more affected than high-latitude ones because of their exposure to higher natural levels of UV-B? Alternatively, do high-latitude systems have a higher capacity of recovery (resilience) than low latitude ones because of their adaptation to extreme environmental stress?
4. May the grazing rate depression (produced by UV-B) compensate the primary production depression caused by UV-B?
5. Is there a significant effect of UV-B on the nutrient recycling in marine system?
6. Have photochemical reactions of UV-B with pollutants synergetic effects on primary and secondary producers?
7. Have food production variations caused by UV-B had a significant effect on the socio-economic system?

Apart from the initial direct fear expressed during the first meeting that increased UV-B levels would deter tourism, the group did not identify synergetic or negative socioeconomic impacts of UV-B on the marine or marsh sectors. The direct impacts of increased UV-B levels on the local economy through tourism and health remained the focus of the socioeconomic interests.

The third question was as follows: *Does the response of UV-B on human health and ecosystem health change with temporal and spatial scale?* Is it possible to study global long-term trends by extrapolating from local characteristics and short-term events, such as UV-B peaks? Rather than choosing between short-term and local effects or long-term global effects, the group tried to accommodate both approaches and reflect on how they are interrelated, using time lags as connectors. For example, there are concerns that the thinning of the ozone layer in the Antarctic will have an impact in the Arctic after a time lag.

The radiation experts agreed that a general global change of 4% over 10 years in ozone depletion was observed. This number is different for high latitudes and low latitudes and there are strong seasonal influences. The UV-B peaks occur on a scale of hours or even minutes. It was decided to model UV-B radiation during springtime in the southern hemisphere with a time step of 1 month to simulate UV-B peaks probabilistically for each of the months. The compromise was to include peaks and still have a long-term focus. The model was to run for 80 years (1970–2050) in order to simulate the possible recovery of the ozone layer expected because of the Montreal Protocol (17).

The fourth question was as follows: *How does the time lag between chlorofluorocarbon (CFC) release and recovery of the ozone layer, ecosystem responses and human health effects manifest themselves?* Do the predicted ozone recovery scenarios, as envisioned by the Montreal Protocol, seem to materialize? It was determined that the model would be based on two basic simulation scenarios, one with and one without successful CFC reduction expected because of the Montreal Protocol. Initially, responses

Table 7. Comments and a question for future research on UV-B.

1. UV-B is the starting point and is not generated by dynamic behavior at this point.
2. Adjustment of ozone level will be treated exogenously in the model.
3. How do we introduce cloud cover in a statistical way?

Table 8. Questions used to gather socioeconomic data.

1. How many cases of acute skin and eye problems occur at peak UV-B periods?
2. How many people with acute eye and skin problems due to peak UV-B events seek medical attention?
3. How many dermatologists and ophthalmologists are in Tierra del Fuego?
4. What is the population of Tierra del Fuego?
5. How much of these acute cases would be prevented if a prevention/alert program were available?
6. How much would such a program cost?
7. How many days of labor are on average lost per acute case?
8. How much does average labor cost?
9. How should the long-term effects be measured? Skin cancer–Pterygium?
10. Is there an identifiable connection between UV-B and long-term immune system impacts?
11. How many tourists might have stayed away due to the "UV-B scare" in 2000?
12. How large is the Tierra del Fuego tourist industry: number of tourists, average spending per tourist.

were thought to be linear; however, the further this group got into the discussion about different latitudes and climate change issues, the clearer it became that the role of ozone and UV radiation in climate change is not well understood. There may be several nonlinear aspects at play.

The fifth question was as follows: *What is the influence of existing policies at the local and global level?* Are there solutions? The group determined that intergovernmental agencies (such as those responsible for the Montreal Protocol and similar conventions) are responsible for placing limits on ozone-depleting substances and expressed a need for research in support of this topic. At a local level, the group discussed efforts, in the form of monitoring and education, that are geared toward prevention. It was noted that policy action mainly focuses on mitigation of impacts rather than on prevention. The mitigation of impacts, especially those on human health, were considered to be a more important need at the beginning of the program. By 2003, certain local prevention initiatives were in place. One medical professional commented on the low number of acute sun-related problems in her practice and concluded that either people were protecting themselves (prevention) or have become indifferent to sun-related problems (no action).

The sixth question was as follows: *Does global warming need to be in the model and, if so, can global warming be represented by temperature only?* Currently, the level of UV-B in the northern and southern hemispheres is different but it is expected that, when global warming and other effects are more widespread, the problems in the two hemispheres may become similar, after a time lag.

By the fourth day of the first workshop, each of the PIs had a list of questions. Some research questions were already planned and the group could expect some answers by the end of the program. Other questions required literature research. Finally, some questions were generated by the model structure and were included as a basis for new hypotheses (*e.g.* in an ideal funding situation, what would you want to research?) On the other hand, the local stakeholders generated a very practical list of data to gather (Table 8). In general, local stakeholders were interested in gathering socioeconomic data.

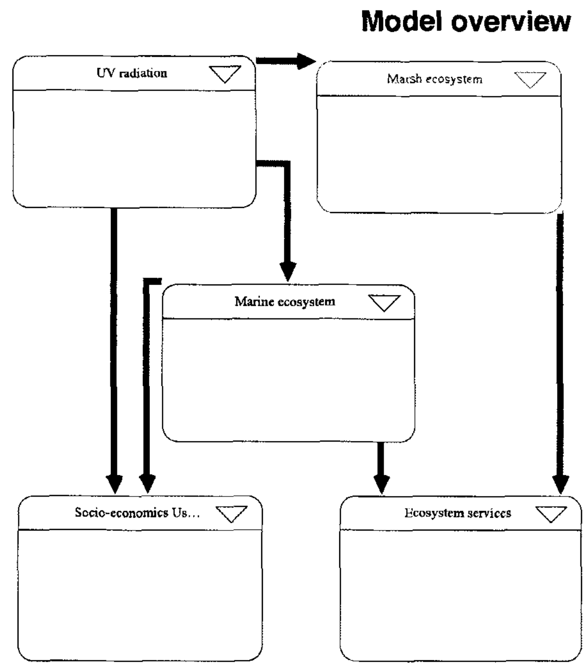

Figure 1. Model overview.

Between meetings. In April 2003 the PIs met in Chascomús, Argentina. The status of the model was evaluated in view of the additional data gathered at the time and the results from ongoing experiments. The PIs decided to emphasize the use the model as a tool to synthesize the research and to expand the findings obtained from experiments to a global scale. As a mid-course change of direction, this approach enhanced the scientific component of the study. The gathering of data to complete and enhance the socioeconomic sector of the model had not been as successful as anticipated during the first workshop. The relationship between the local stakeholders and the modeler remained indirect, with a local PI serving as intermediary.

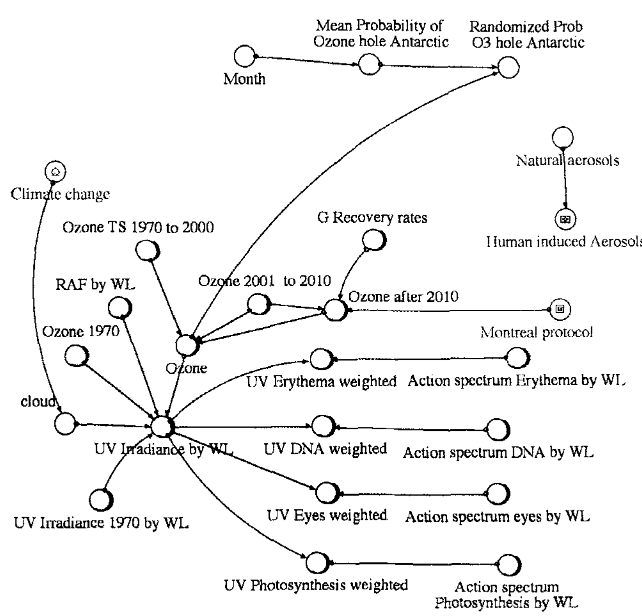

Figure 2. UV-B radiation model sector.

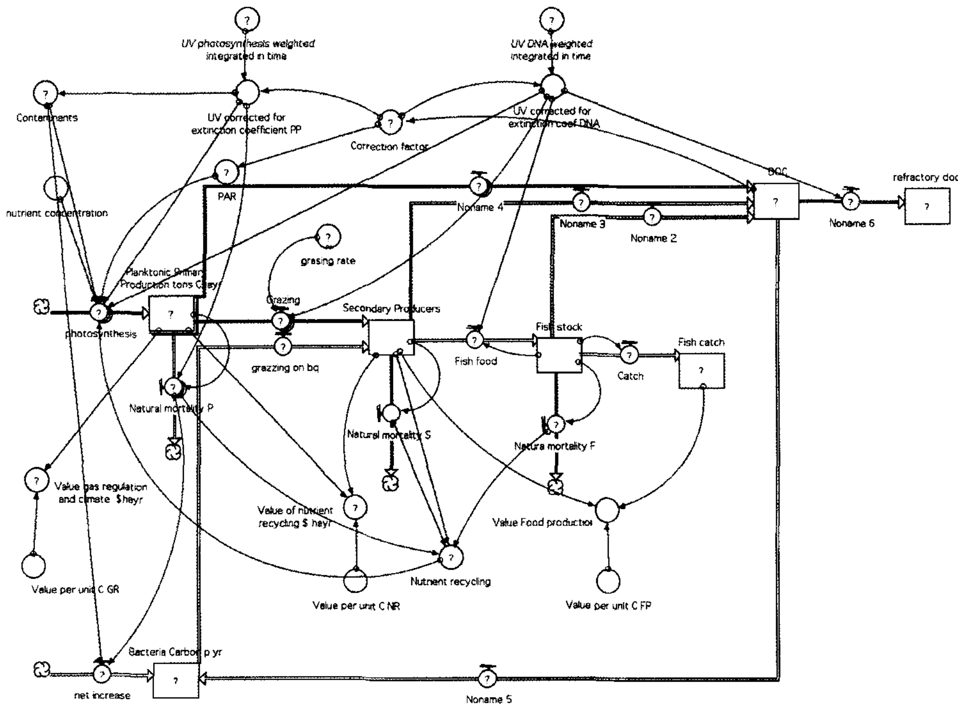

Figure 3. Marine model sector resulting from the first workshop.

Subsequent visits of the modeler to the University of Quebec and to Horn Point Lab (HPL) at the University of Maryland Center for Environmental Science allowed for integration of new data to the marine and marsh systems. The major input of socioeconomic data was based on stakeholder participation at the meetings. Limited access to additional socioeconomic data is attributed to a lack of a more formal structure for data gathering. Local professional stakeholders had data available that would have been valuable if organized in a statistically valid manner. In hindsight, additional funding would have been needed to collect, organize and analyze health data. Although limited additional funds were spent on data gathering efforts, it was not sufficient to cover all needs. Additionally, a midterm meeting specifically designated toward data gathering would have been helpful.

Second workshop. In March 2004 a second meeting took place in Ushuaia. The model was shown, feedback was provided, limited scenarios were presented and the questions the model was addressing were revisited.

The participating PIs were the same as in the first meeting, except for one crucial PI who had a family emergency. Fewer local stakeholders participated in the second meeting. However, one particular local stakeholder became very active in getting the input of additional stakeholders to fill in the gap. A more consistent local coordination of stakeholders is advisable for future collaborations.

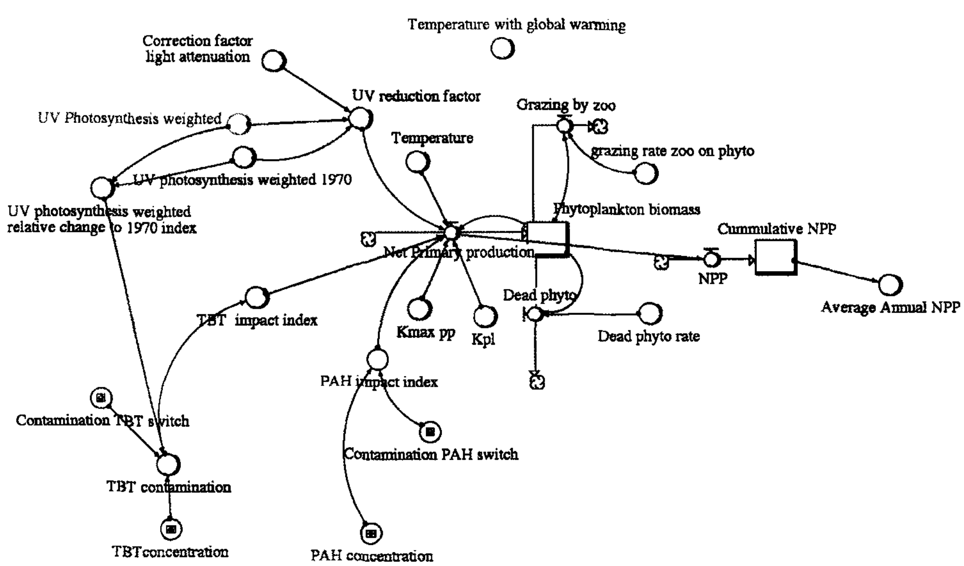

Figure 4. Marine sector model structure after simplification.

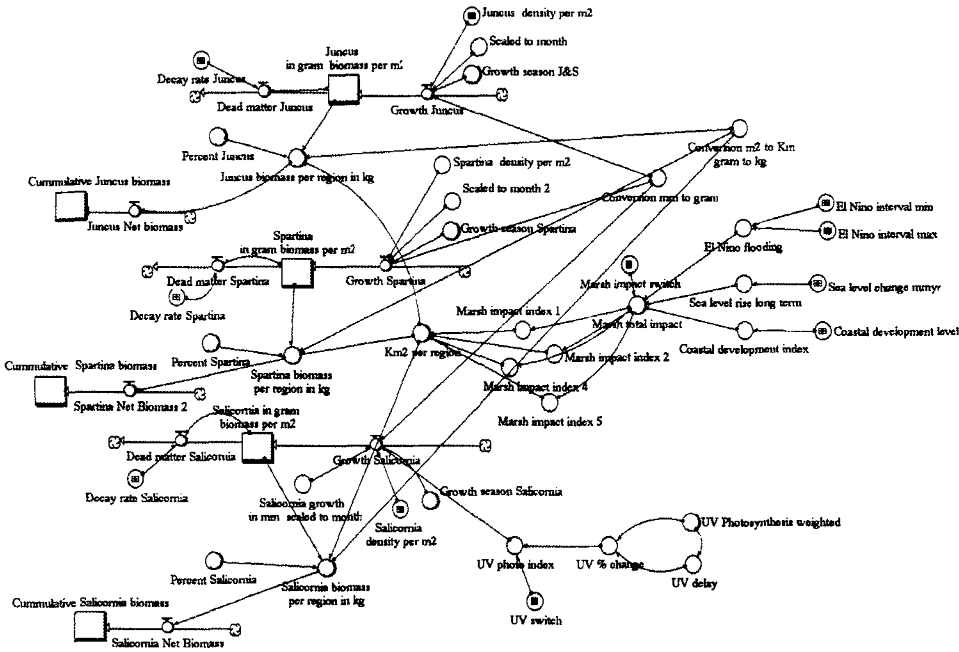

Figure 5. Marsh model sector structure.

A project managed over long distances needs a dedicated local manager or a more active connection with local participants; that is, local participants must be contacted more often and someone with local access must function as a local counterpart. External factors, such as the national economic situation, can also temporarily pull interests away from UV-B issues toward other concerns.

Several important changes in the modeling approach were recommended during the second workshop. The negative influence of UV-B on tourism that had been anticipated during the first meeting had not happened. In fact, the tourist sector was thriving as never before, because of a favorable monetary exchange rate. Peaks in UV-B radiation as a health concern for the local population had decreased in importance. The workshop participants reiterated their interest in long-term trends and impacts of UV-B. Because long-term studies about the impact of UV-B on skin, eyes and the immune system are often controversial, the

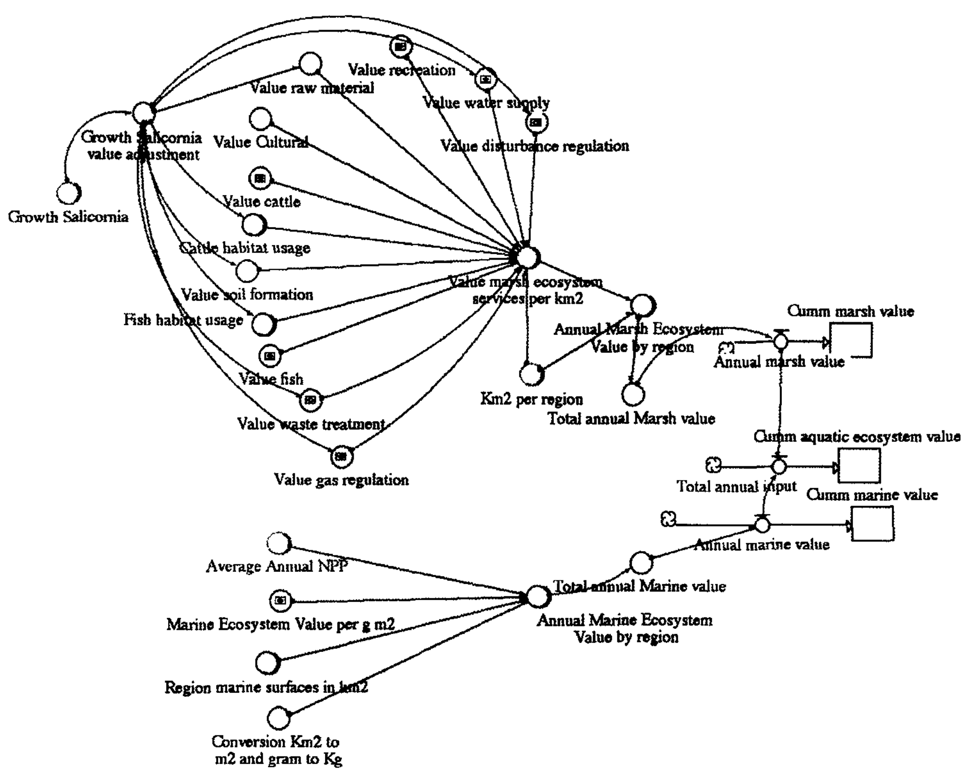

Figure 6. Ecosystem service values sector.

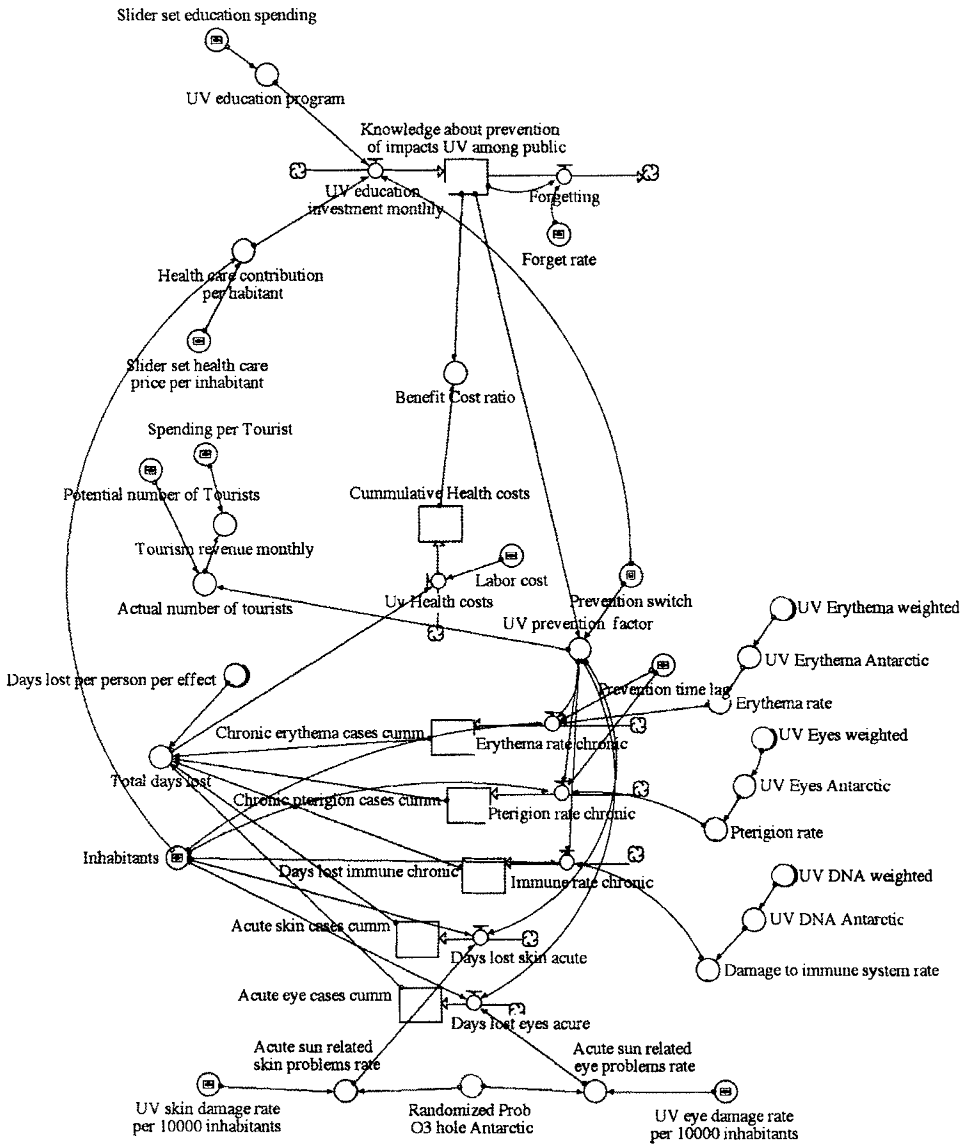

Figure 7. Socioeconomic sector for Tierra del Fuego.

socioeconomic sector of the model became more speculative. Furthermore, reduced input from stakeholders into the model had a negative impact on this sector. The local socioeconomic component did not gain additional substance and remained a reflection of conceptual thinking and back-of-the-envelope calculations and estimations.

Model construction. The original intent of the mediated modeling component was to function as a bridge between local stakeholders and scientists in order to extend the research in a practical frame and attempt to make it usable for professionals and policy makers. Ushuaia was chosen as a pilot area because UV-B issues were on the public's mind in 2000. The shift in emphasis from local issues to global issues was discussed.

The conceptual model structure that resulted from the first meeting was relatively well accepted by the group and encompassed much good thinking and discussion. The final version of the model was modified in some areas to account for existing data and to capture the most basic concepts (available at: http://www.mediated-modeling.com or http://www.iai.int/ [the IAI Web site]). A brief description of the model that ultimately resulted from the workshop process follows.

The model was built with STELLA (High Performance Systems Inc.). This software is well suited for systems dynamics studies. It uses four basic iconic building blocks: stocks, flows, auxiliary variables and connectors, which are identified in the model structures as rectangles, valves, circles and arrows, respectively.

Figure 1 provides an overview of the model. The model contains five main "sectors": UV radiation, which calculates the amount of UV-B radiation reaching the surface of each of the five latitudinal zones each month; marsh and marine ecosystems, which calculate the responses of these ecosystems in each latitudinal zone to the radiational forcings for each month; ecosystem services, which calculates the impacts on a range of ecosystem services of the changes in marsh and marine systems in each latitudinal zone for each month; and socioeconomic impacts, which calculates the tourism and health impacts (for Ushuaia in this example).

Figure 2 shows the UV radiation sector of the model. Irradiances in regions I and V present large latitudinal variations due to dif-

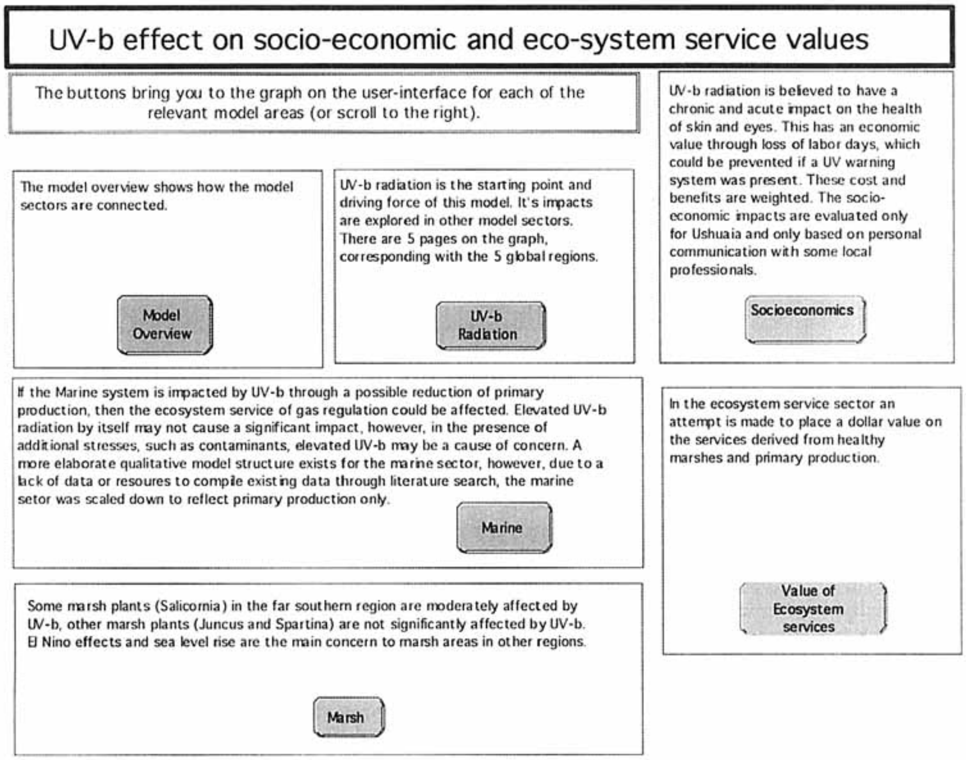

Figure 8. Main navigation screen.

ferences in ozone depletion and SZA variability, whereas the gradient is much smaller in the other regions.

This model sector simulates trends in UV-B irradiation, using data on monthly ozone levels and the action spectrum for photosynthesis, DNA damage, erythema characteristics and impact on eyes. There are two future scenarios: one with and one without recovery of ozone level by 2050. The irradiation peaks are simulated probabilistically. Action spectra for UV-B effects on photosynthesis (30), for erythema characteristics, for DNA damage and for the impact on eyes are used as weighting factors. The respective UV-B-weighted parameters are used in the other model sectors. The equation for UV-B irradiance per wavelength (WL) is:

$$\begin{aligned}&\{[\mathrm{Ozone\_1970(Arctic)/Ozone(Arctic)}]\\&\quad *\mathrm{EXP[RAF\_by\_WL(Arctic, High\_310)]}\}\\&*\mathrm{UV\_Irradiance\_1970\_by\_WL(Arctic, High\_310)*cloud}\end{aligned}$$

Figure 3 shows the marine model sector that resulted from the first workshop. The original goal was to model how the impacts of a change in community structure due to UVB would cascade to the bottom of the food chain. The present structure, shown in Fig. 4, was considered to better represent one of the main scientific conclusions of this group: the synergistic effect between certain pollutants and UV-B (31,32). The model addresses the possible consequences of these findings for the global CO_2 budget. The model expresses possible consequences of changes by UV-B effects in terms of ecosystem service values, based on the findings of Costanza *et al.* (33).

Figure 5 shows the marsh sector, with an emphasis on *Juncus*, *Spartina* and *Salicornia* species as representative marsh plants. *Salicornia* is mainly affected by UV-B because its actively growing cells (the meristems) are apical, whereas the meristems of *Juncus* and *Spartina* are at the base of the plant and are therefore relatively protected against the influence of UV-B by the canopy (9). Since the area covered by *Salicornia* in the subAntarctic region, where the UV-B fluctuations are most severe, is relatively small compared with the area covered by *Juncus* and *Spartina* elsewhere, the model does not show significant impacts of UV-B on marshes. This may be an inaccurate general assumption, considering that *Salicornia*'s specific function in the marsh community may be underestimated in other regions.

Figure 6 shows the ecosystem service values of the marine and marsh systems. For the marine sector the ecosystem services are based on net primary production (NPP) and values are extracted from the report by Costanza *et al.* (34). The investigators attempted to calculate new values for marsh ecosystem services and determined additional uses and economic activities for marshes. All values are estimates (9).

Ecosystem services are a constructive way to link different ecosystems and their contributions to human welfare. However, the understanding of ecosystem services in dynamic terms is, in general, still in its infancy and requires much further research (36). This model sector allowed us to sum up all the impacts of UV-B for the marsh and marine systems and express these impacts in dollar terms.

Figure 7 shows the socioeconomic sector for Ushuaia. Acute and chronic impacts of UV-B radiation are translated into possible lost labor. The main approach was to prevent impacts through education to promote protection and it was modeled on the basis of the time lag of ozone recovery. A feedback loop to further the reduction of ozone-depleting substances was discussed but not modeled. No good data are presently available to calibrate this sector and the model structure remains speculative.

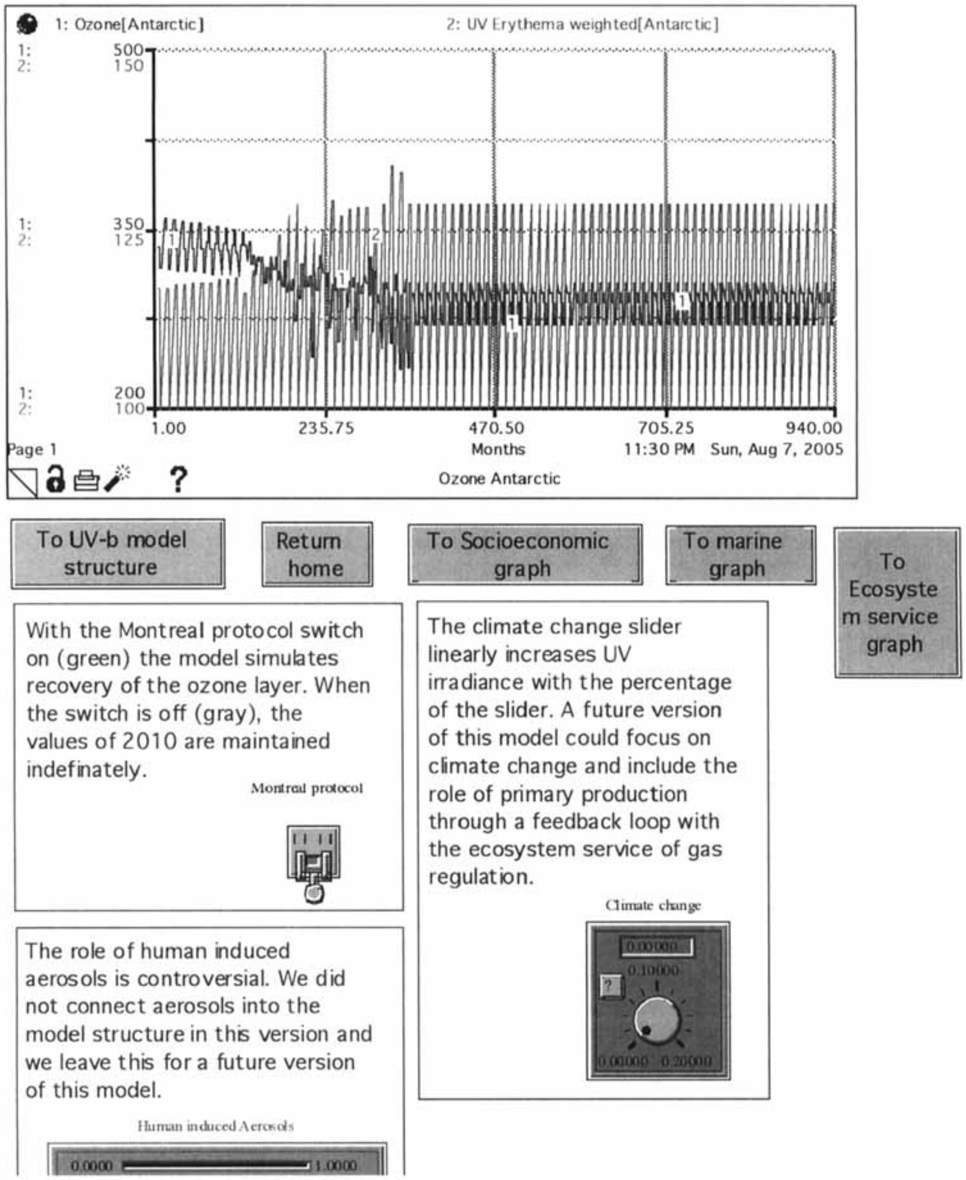

Figure 9. UV-B output screen.

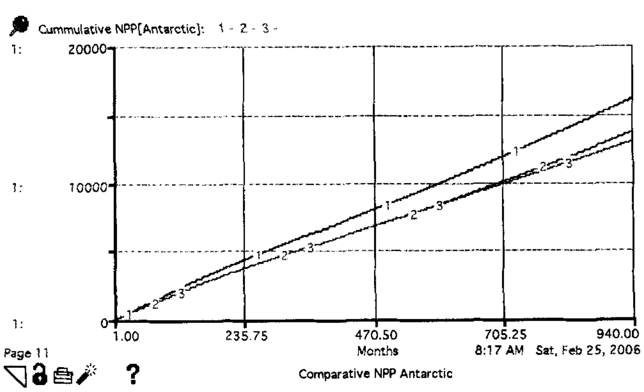

Figure 10. Cumulative net primary production (NPP) in the Antarctic region (lat 90–55°S) under three scenarios: (1) without pollutants and with the Montreal Protocol scenario evolving as anticipated; (2) with pollutants and the Montreal Protocol evolving as anticipated and (3) with pollutants and ozone levels not recovering according to the Montreal Protocol predictions. Data are specified in grams carbon per square meter per month.

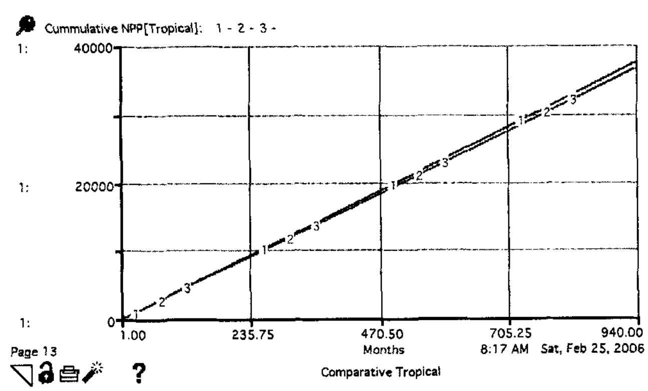

Figure 11. Cumulative net primary production (NPP) in the tropical region (lat 20° S to lat 20° N) under three scenarios: (1) without pollutants and with the Montreal Protocol scenario evolving as anticipated; (2) with pollutants and the Montreal Protocol evolving as anticipated and (3) with pollutants and ozone levels not recovering according to the Montreal Protocol predictions. Data are specified in grams carbon per square meter per month.

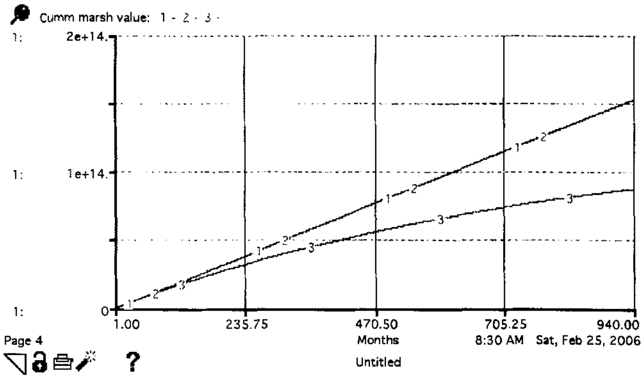

Figure 12. The cumulative monthly value of ecosystem services of the global marsh area under a scenario of (1) no UV-B impact and no increase in sea level, (2) UV-B impact and no increase in sea level and (3) an increase in sea level. Data are specified in US dollars.

A comparison of the two ecosystems considered in the model revealed that, although changes in the marine sector due to anthropogenic influences may *affect* global climate change, marshes are expected to primarily be *affected by* climate change. Marsh ecosystem service value is partly derived from disturbance regulation. Marshes cover relatively smaller areas than oceans but have a high ecosystem service value per hectare. The value of marine ecosystem services is lower per hectare but the area is so vast that the global value for the marine area arguably comes out higher than for global marshes.

Model behavior and scenarios

The modeling effort was an exercise to synthesize data and to obtain knowledge and new research findings. Even though the model is based on data, during model building we emphasized reasoning of the scientists and stakeholders and de-emphasized present knowledge based on published data. This approach makes the model's scientific output less reliable but an ideal tool to generate new hypotheses. Thus, the two sections evaluating modeling behavior and possible scenarios are based on qualitative, not quantitative, considerations. Furthermore, because of the lack of calibration data the model represents more the implications of the shared assumptions of the participants than it does a technically calibrated description of the system's behavior. In other words, the model's credibility (at this stage) is derived more from the buy-in of stakeholders than from good fit with observed data.

Model behavior. We describe here the general behavior of the model, some of the major uncertainties and some of the ways the stakeholders wished to exercise it to derive answers to their questions. To accomplish this we will go through each of the output screens that were designed for each of the model's sectors and briefly describe how they were set up and what they show.

On all of these figures, "buttons" are shown, which take one to the area of the model indicated on the button. "Sliders," "switches" and "knobs" are also shown, which allow the user to change the value of the parameter shown.

Figure 8 shows the home navigation screen that explains the main sectors of the model and provides buttons to navigate to each sector. For example, if one clicked on the button labeled "UV-B radiation" in Fig. 8 one would go to Fig. 9, which shows the output screen for that sector. Figure 9 shows a switch for turning on or off the Montreal Protocol, a slider (not yet implemented) for setting the level of human induced aerosols and a knob for adjusting the level of UV radiation. The graph shows the level of ozone in the Antarctic latitude zone, along with the level of UV at the surface weighted by its impact on erythema. Many other graphs are accessible by clicking on the tab in the lower left corner of the graph. The time scale is in months on these graphs, going from 1 (in 1970) to 940 (in 2050, 80 years later).

Scenarios. Although the combinations of parameters to design alternative scenarios are numerous, the following scenarios best illustrate the conclusions of the marine system.

Consider the monthly value of ecosystem services of the marine area in the Antarctic and tropical regions under a scenario (1) without pollutants and with the effects of the Montreal Protocol evolving as anticipated, (2) with pollutants and the effects of the Montreal Protocol evolving as anticipated and (3) with pollutants and ozone levels not recovering according to Montreal Protocol predictions. Projected cumulative NNP in the Antarctic and tropical regions under identical scenarios shows that the effect of pollutants is more damaging than the effect of increased UV-B due to ozone depletion (Figs. 10 and 11). Phytoplankton can acclimate to UV-B levels corresponding to 60% ozone depletion under conditions of mixing in the water column (11,31,36), thus maintaining high biomass and primary production. This is observed at all latitudes (10). Acclimation is achieved by changes in community structure, in which resistant species become dominant. High abundance of UV-absorbing compounds and photoprotective carotenoids characterize UV-B–resistant species (37).

The impact of pollutants is equally strong in both regions but the synergetic impact of UV-B is felt more strongly in the Antarctic. In the 2050 the ecosystem service value lost 20% between scenario 1 and 3 in the Antarctic and 3% in the tropical region.

The cumulative monthly value of ecosystem services of the global marsh area are calculated under a scenario of (1) no UV-B impact and no sea level rise, (2) UV-B impact and no sea level rise and (3) a sea level rise impact (Fig. 12). Increased sea level is the primary factor diminishing ecosystem services, because the most common marsh plants (*Juncus* and *Spartina* species) are not sensitive to UV-B radiation (9). The third species considered is UV-B sensitive. However, *Salicornia* is not abundant in the Antarctic region, which has the largest variation in UV-B radiation.

In both ecosystems the largest impact on the modeled variables chosen to represent ecosystem services values was due to factors not related to UV-B impacts. Plants, both in the ocean and in marshes, can acclimate in order to minimize UV-B damage. As UV-B has been a major stress factor during the evolution of organisms, plant communities seem to be able to adapt successfully to increased radiation as to maintain intact ecosystem function.

CONCLUSIONS

The model includes several synthesis results from the mesocosm studies (39). During the first workshop recommendations were geared toward an increase in information provision and education about mitigation options, because of the importance of short-term challenges recognized by the local stakeholders in Ushuaia.

The scientists advocated investment in basic research, because many pieces of the puzzle are still missing and cannot be resolved within the scope of this program. The group agreed that a strengthening of the links between research, education and policy should be sought.

In the final meeting short-term effects were less of an issue and the short-term challenges and long-range issues were of more interest. The focus of the PIs had moved toward climate change issues, with UV-B as one additive stressor (or possibly a moderating factor). The importance of relating UV-B effects in a context of other global change variables became apparent.

The ecosystem service value of marshes is high per unit area but the area of marshes is relatively small. The marine area is large with a much lower value per unit area for ecosystem services. However, there may be significant value impacts that warrant more research into the dynamics of global climate change and ecosystem services on both ecosystems. Group model building may continue to be helpful in assisting interdisciplinary groups to think about these complex interrelated issues.

The synthesis model reflects the conclusion for the marshes that UV-B on a global scale is not a significant stress relative to potential impact of increases in the sea level (9). Marshes are thus affected by global change.

The synthesis model reflects the conclusion of the marine group that a potential impact of a systemic order at a global level may be present. Enhanced UV-B could cause a shift from primary producers to bacteria at the community level. This may impact the global carbon cycle. The effect is increased in the presence of certain pollutants. Enhanced UV-B effects affect global change by potentially affecting CO_2 levels in oceanic surface waters.

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